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SOME OBSERVATIONS AND EXPERIMENTS ON JOINT PLANES[1]

PEARL SHELDON

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[1] This was done as part work for a Ph.D. degree at Cornell University. Acknowledgments are due to Professors R. S. Tarr and G. D. Harris for information and criticism.

I

INTRODUCTION

In an attempt to find the age of the joint planes of the Ithaca region with reference to the low folds which occur here, observations were made on 3,046 joints. Nearly all of these readings included both strike and inclination, although in a few cases one or the other was necessarily omitted. Over six hundred readings were made in the Fall Creek gorge at localities 55 to 58 and part of 54 in Fig. 7. For this distance readings were made on every accessible joint which was strong enough to show for two or three feet and not so variable that the data would be of little value. Occasionally observations were made on more poorly developed joints which were locally characteristic.

Although later work showed that this locality was hardly typical in some respects, this study showed how the joints of a single area vary with their strike and formed a basis for later work by showing which sets of joints are constant and strong and which too variable and weak to be of value in comparing different localities. During one summer and fall about two thousand readings, including this six hundred, were made in the Ithaca region. The following winter was given to experimental work and examination of the data already taken, and during the next summer another thousand readings were made in completing the section and investigating points connected with the theory, particularly the faulting.

Only a part of even the master joints could be read in the field but those were chosen which local observation and work in neighboring areas showed to be most characteristic for each place and, because of their constancy, most valuable for comparison with other areas. The work was begun without a conviction in favor of any one of the theories for the formation of joints and most of the evidence of their age was unexpected, so that the choice of readings was influenced little by preconceived ideas.

The data had a bearing on several points besides the age of the joints. The following are some of the results obtained:

Nearly all the uniform and strong joints fall into two groups.

Those in one group strike nearly parallel to the axes of the folds and form the strike set.

Those in the other group strike approximately along the dip of the rocks and are the dip joints.

The dip joints form two distinct, similar sets and appear to vary with the pressure which caused the folding.

The strike and dip joints are usually nearly vertical and a single joint varies little in strike and inclination at any exposure. The joints belonging to each set have a range in strike of only a few degrees at any one locality.

A set of joints making a moderate angle with the strike set is locally strong but these are not of the same character as the strike and dip joints. They are more variable in strike and inclination and usually have a greater hade.

Joints striking between the major sets are common but are usually weak and very variable with little apparent system. Their hade is usually large. In some localities the highly inclined joints are strong.

The master joints were evidently formed during the earlier part of the folding which took place here during the Appalachian Revolution. They are not younger than the faults which were formed at that time, since they are displaced by the faults. The hade of the strike joints shows that they were not formed before the folding. The dip joints vary with the folds and the forces active during the folding and were apparently formed at that time.

By compressing blocks of paraffin and resin various systems of cracks were obtained. Some were like those obtained by Daubrée. The finest cracks were nearly parallel to, and at right angles to, the pressure.

The observations support the shear theory of the formation of joints by indicating that the joints here were formed while shearing stresses were active and that the joints vary with those stresses. The joint planes, however, are nearly at right angles to the fault planes and are very unlike them, so that the theory that joints are incipient faults is not supported. Some factor like shock may have determined the position of the breaking planes which are classed as joints.

FOLDING

In general the rocks of the Ithaca region dip slightly to the south so that successively older strata are exposed to the north in the lake section. In the area studied the outcrops are Hamilton shale, Tully limestone, Genesee shale, and Portage sandstone and shale. The southward dip is not uniform, however. The region is crossed by a series of low folds which have been described and mapped by E. M. Kindle.[1] They have been more briefly described by H. S. Williams,[2] and one of them by S. G. Williams.[3]

In the Watkins Glen–Catatonk quadrangles the anticlinal and synclinal axes occur a few miles apart and their directions are usually somewhat north of east. The folds die out east of the longitude of Ithaca. Three of these axes—the Enfield syncline, Watkins anticline, and Corbett Point syncline—cross the Ithaca region. They are shown in Fig. 6, copied from *Folio 169*. The dotted lines represent approximate location. North of these axes and beyond the northern boundary of the area included in *Folio 169* is a well-developed fold which is conspicuous along Cayuga Lake because it is outlined by a prominent outcrop of Tully limestone. The point where the anticlinal axis crosses the western shore is accurately shown by a hard layer in the Hamilton shales which rises a few feet above low-water level at the highest point of the fold. The highest point on the eastern side is not so well shown but the direction of this axis as drawn in the upper part of Fig. 6 is correct to one or two degrees. It is a pitching fold. S. G. Williams gives the height of the Tully limestone outcrop on the west side as 160 feet and on the east side 235 feet above lake level. This has been called the Ludlowville fold and the Shurger Point fold.

From this axis the rocks descend to the northern limit of the map but the dip is not uniform. First there is a sharp dip, then a nearly horizontal region, then another steep dip to the north, thus forming a small fold on the northern limb of the main anticline.

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[1] *Jour. Geol.*, XII, No. 4 (1904), 281–89; *Folio No. 169, U.S. Geol. Surv.* (Watkins Glen–Catatonk quadrangles), pp. 13–15; field edition pp. 98–107.

[2] *Proc. Am. Assoc. Adv. Sci.*, XXXI (1882), 412.

[3] *Am. Jour. Sci.*, 3d ser., XXVI (1883), 303–5.

The axis of the small anticline probably lies just south of the mouth of Taughannock Creek and the axis of the corresponding syncline about half-way between the mouths of Taughannock and Willow creeks. This fold is present on the eastern side of the lake but its axes were not determined there.

In the Inlet Valley the Watkins anticline is similar to the fold just described. It is represented by nearly horizontal rocks on the northern limb and inclined rocks on the southern limb. Further west, at Seneca Lake, the fold is stronger, with northward dips in the northern limb. South of the Enfield syncline is a strong anticline which reverses the dip.

In the area studied, therefore, there are three anticlines and three synclines with the Shurger Point fold the most strongly developed. The other two folds are represented by changes in the inclination of the beds without reversal of dip on each limb of the larger fold.

The dips of these low folds in southern New York range from 0° to 10° and are usually small. Though weak, the folds are persistent and are nearly parallel to the high mountain folds south of the Pennsylvania line. There seems no reason to doubt Kindle's conclusion that they were formed during the Appalachian Revolution. No folds of any other date are known here, so that the structure is comparatively simple. Broad warpings like that described by M. R. Campbell[1] apparently have not affected the problem of the joint planes.

FAULTING

Kindle[2] described a few small faults of variable character in the Watkins Glen–Catatonk quadrangles. G. C. Matson[3] mentioned several cases of movement along bedding planes and minor thrust faulting. He found that the dikes which cross some of these slipping planes were displaced, the maximum displacement given being two feet.

The ordinary type of faulting in this region is nearly horizontal thrust faulting with small displacement. These faults are numerous, occurring by the score in the shale beds, especially in the Hamilton shales. Often several may be seen in the height of a single cliff. Since these faults do not, as a rule, cross bedding planes the amount of movement is indicated only by the displacement of the joints, which are nearly at right angles to the faults. Whether or not this shows the total movement depends upon the relative ages of the joints and faults. Perhaps some faulting took place before the joints were formed. The displacement is usually between a fraction of an inch and seven or eight inches. Four to six inches is common and a single outcrop of a fault will sometimes show progressive variation through almost the entire range of displacement found in these faults. In other places the displacement is nearly constant for rods.

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[1] *Bull. Geol. Soc. Am.*, XIV (1903), 277–96.

[2] *Folio 169*, p. 15; field edition, p. 108.

[3] *Jour. Geol.*, XIII, No. 3 (1905), 264–75.

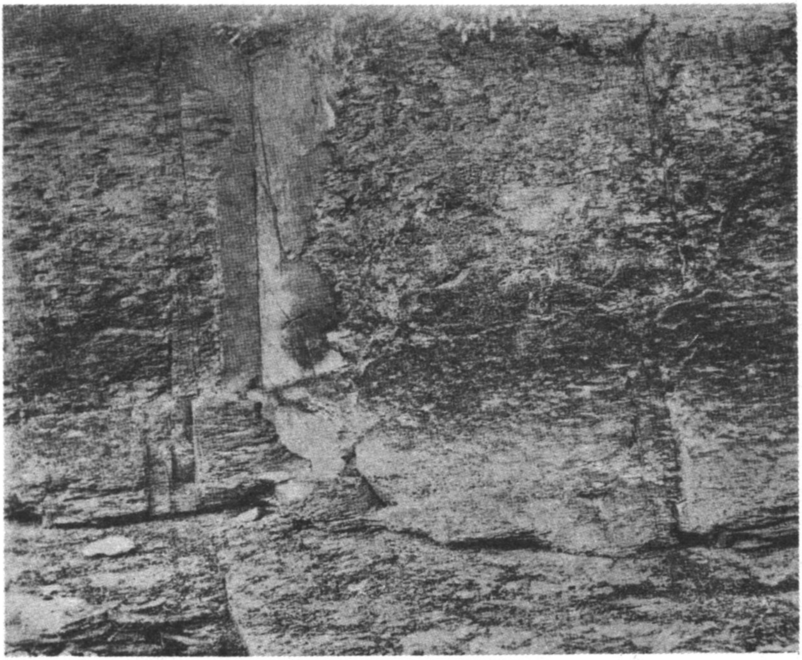

FIG. 1.—Two faults in the Hamilton shales. The eroded horizontal line is the lower fault. The upper fault descends to the left.

One of the best faults seen in the Ithaca region is in the Hamilton shales where Salmon Creek falls over the Tully limestone back of Ludlowville. It passes around the base of the fall, just above the level of the pool, disappears beneath débris, then reappears and continues downstream just above the creek bed for many rods. It is made conspicuous by stream erosion along the fault line.

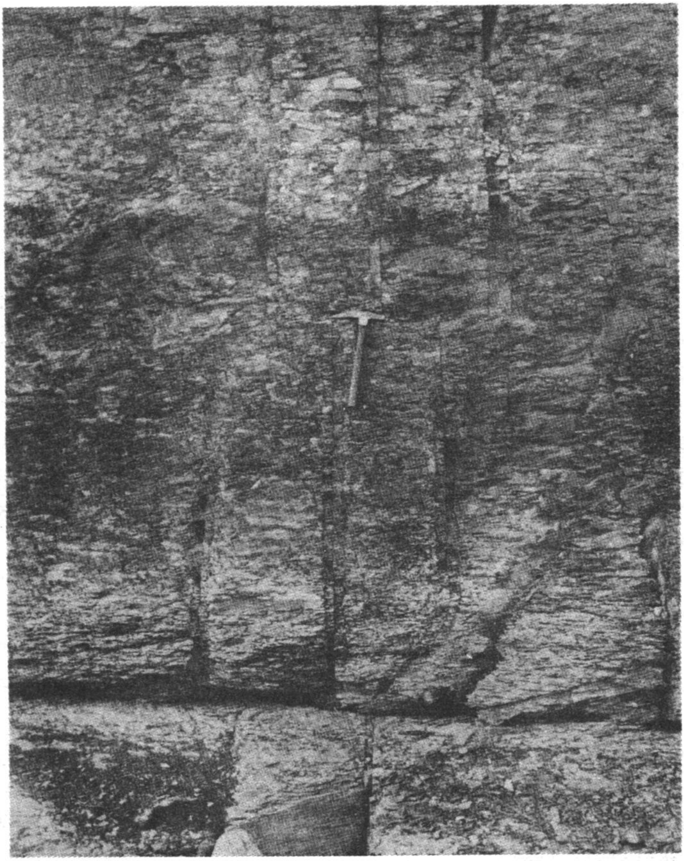

FIG. 2.—Right-hand continuation of the faults shown in Fig. 1. The head of the hammer shows the movement along the upper fault.

To casual observation these faults look like weak, slightly weathered bedding lines. Inspection shows the displacement of the joints across them and where they are exposed to stream or wave cutting they appear as considerably eroded lines, sometimes worn into tiny caves. Figs. 1 and 2 show two of these faults in the cliff beside the bridge where the highway enters Ludlowville from the south. The photographs are of adjacent portions of the cliff. The lower, nearly horizontal, fault is eroded by the creek which is cutting the cliff. The upper fault, which has an unusually steep angle, has a fresh exposure and is therefore inconspicuous. The displacement along the upper line is shown by the head of the hammer. The movement has been such as to thrust the central wedge-shaped mass to the left and into the cliff between the upper and lower parts of the rock.

The exact direction of movement in the horizontal faults of the Ithaca region was not determined. Something might be learned from the relative amount of displacement of the different sets of joints but this method might be subject to error because of difference in the time of formation of the different sets. In the cases observed there was not a conspicuous difference in the displacements of the different sets, indicating that the direction of thrust made a fair angle with each set there present unless much of the movement took place between the times of formation of the different sets.

The comparative behavior of the faults in soft and hard rocks is interesting. In the Hamilton shales is a hard encrinal layer a foot or two in thickness. This is shown in Fig. 3. It did not yield to pressure without breaking so readily as the adjacent shales and the exposures of this layer along the lake show faults every few feet. They soon die out after entering the shale. Fig. 3 is a photograph of two faults at locality 14, Fig. 7. The slipping surfaces of the faults in this layer are much slickensided. The vertical displacement along these faults is from a fraction of an inch to three inches.

At locality 14, Fig. 7, where the encrinal layer rises above water level, the strike of eight faults was found to vary from N. 70° W. to due W. with an average of N. 76° W. At locality 39 in the same layer eight faults varied from N. 65° W. to S. 89° W., with an average of N. 72° W. The strike of the majority was from 20–25° north of west. At locality 9 where the encrinal layer passes beneath the lake level two readings were N. 86° W., two N. 84° W.,

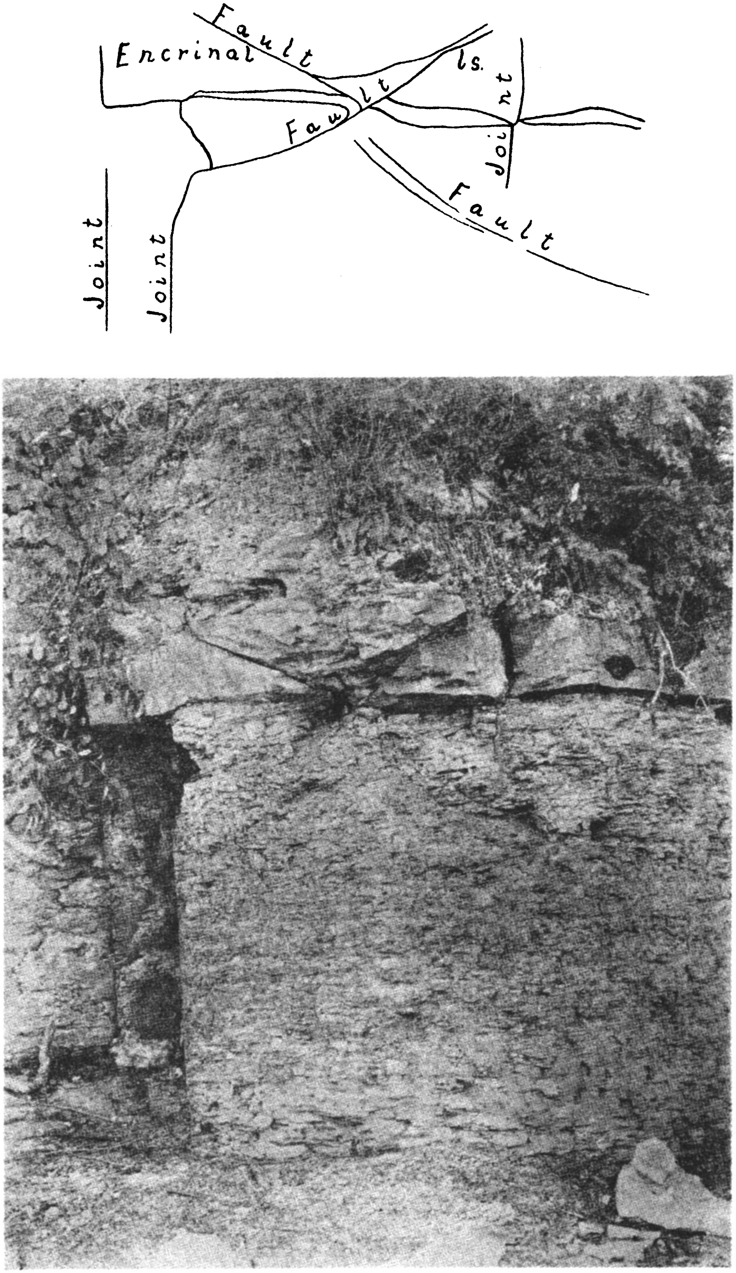

FIG. 3.—Symmetrical faults in the encrinal limestone

and one N. 80° W. These were the best seen for measurements, since one face of the faults had usually fallen away and the direction of movement could be read directly from the strong, even striations on the slickensided surfaces. Many other faults in this layer were seen but were inaccessible for measurement. The inclination of these faults is sometimes south and sometimes north and the angles are nearly the same in the two cases, making the faults symmetrical about a nearly horizontal plane. In the readings made the hade varied from 45° to 75°, but most were near the average, which was 62°. These faults usually continue for a few feet in the adjacent shale, but instead of continuing with the same hade they flatten out and become nearly horizontal as in the shales where no hard layer is present.

Since the faults of this region are usually nearly horizontal it might be expected that where well-developed bedding planes are present the slipping would take place along these. This is not true in the case of the encrinal layer. The unusually steep angle of the faults there seems to be due to the hardness of the rock, which has more influence on the location of the slipping planes than the presence of planes of weakness along the stratification. Some of the best of the horizontal faults were in nearly homogeneous shales, not along bedding planes. Evidently the bedding planes do not control the angle of the faults.

It is probable that the strike of the faults in the shales is about the same as that of the small faults in the hard layer which could be measured. It is noticeable that the strike varies from the direction of the axis of the fold by a rather large angle and that this angle increases eastward with the rise of the pitching fold. The faults were probably formed at the same time as the folds, that is, during the Appalachian Revolution, since no other disturbance of sufficient strength to produce these uniform faults is known here. The faults show that the direction of the local resultant force varied considerably from the general direction of the active force which produced the folds if the axes of the folds are at right angles to the latter. The explanation seems to lie in the pitch of the folds. Localities 9, 14, and 39 are in an anticline which rises rapidly to the east. The direction of movement points in toward the center of a domed anticline looking from the south whence the active force came. Apparently the strike of the faults is about parallel to the strike of the rocks on the southern limb. If the pitching of a fold is due not to a variation in the active force causing folding but to a variation in the rigidity of the rocks, the molecular return forces in the soft rock near the center of the dome would not be so great as in the harder rock near the saddles and movement toward the dome might be expected. The exact analysis of the faulting is a problem in shearing closely connected with the shear theory of jointing.

OBSERVATIONAL WORK

JOINT PLANES

In measuring the joints a compass with a four-inch needle and open sights was used. The deflection of the needle from true north was taken roughly as seven degrees west. No attempt was made to read to less than a degree. The accuracy of the readings depended upon the character and exposure of each joint. The observations on most of the master joints were accurate to one or two degrees, but for the variable minor joints of large hade the error might be from five to ten degrees. The hade was measured with a six-inch protractor to which a lead was attached by a thread. Wherever possible the measurements of hade were made from such a distance that the edge of the protractor covered nearly the whole height of the exposure in order to obtain a good average. The readings were usually made to one degree. The master joint readings were mostly correct to one degree but for minor joints the error might be several degrees.

FALL CREEK JOINT PLANES

In the upper part of the Fall Creek gorge all accessible joint planes except the smallest and most variable were measured. Fig. 4 shows the orientation of these joints. The readings are tabulated by the method used by Professor Tarr for the joints of Cape Ann.[1] The strikes are divided into groups of three degrees, each beginning at the west so that the outer rays are N. 90° W.–N. 88° W. and N. 87° E.–N. 89° E. The figures in the margin give the number of readings to each group of compass directions. Fig. 4 shows that in direction the joints fall conspicuously into groups or sets. One set whose strike is usually between N. 70° E. and N. 80° E. is strong and nearly constant in direction and hade. Although the extreme readings of strike in this set vary by twelve or thirteen degrees the majority fall within four or five degrees. The hade is also nearly uniform. At locality 57, one hundred forty-six joints belonging to this set were measured. The total range of hade was from 6½° S. to 9° N., but only two of the entire number showed an inclination to the south and most of those to the north fell within a range of a very few degrees. This set is well developed at Forest Home, locality 57, but not elsewhere in Fall Creek. Localities 55, 56, and 58 afford only a few readings and those not very good. This set is best developed in the shale beds, and the variation with the character of the rock may account for its presence at Forest Home, where shale beds are common, and its poor development in the more sandy layers above and below. The joints of this set strike nearly parallel to the strike of the rocks and form the set known as the strike joints.

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[1] *Ninth Ann. Rep. U.S. Geol. Surv.*, 1887–88, pp. 583–88.

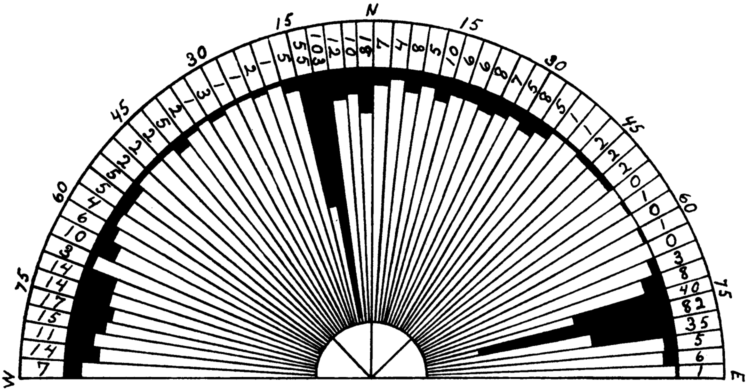


FIG. 4.—Tabulation of the strike of the Fall Creek joint planes

Nearly at right angles is another set most of whose readings are between N. 10° W. and N. 15° W. They represent the set called dip joints. These joints are strong, especially in the sandy layers, where they are conspicuous. As in the strike set, the hade is small and uniform. In a single small area the strike of the dip joints varies less, perhaps, than the strike of the strike set, but from place to place the variation is greater. Farther down the creek the average angle with the north is smaller. In upper Fall Creek there is little evidence of a second dip set, common elsewhere, which makes a small angle with the set just described. In Fig. 7, locality 55, is shown the average of some poor joints which may belong to this second dip set.

Besides these, certain joints with much more variable strike between 60° W. and W. might be considered as a set. In some places where the strike set is weak this set has a development which, though less regular than in the strike and dip sets, is quite strong and distinguishes the set from the mass of small joints. The hades are usually larger and less uniform than in the strike and dip sets. These joints are often curved and the smaller ones, especially at Forest Home, often show a sigmoid horizontal outcrop with the hade varying from one side to the other with the curve.

The rest of the joints of this area may be classed as weak and variable. For thirty degrees east of north the variable joints are more common and may be due to the tendency for a major set to form in that direction, but in the upper Fall Creek gorge they do not form a recognizable set. Variable joints a foot or two in length strike toward every point of the compass. Their hade is usually high, from 30° to 60°, and as a rule both the strike and hade vary over even the small extent of these joints. Enough readings were made on these to indicate their general character. They are common, but unimportant in comparing the variation of the joints with the folds.

The study in Fall Creek showed that joints of all directions are present but that those of different directions vary greatly in character. There are two sets in which the individual joints are strong and, what is more important, each joint is nearly the same throughout its extent and the joints of each set are nearly constant for one locality. It was apparent that these could be used in comparing different areas but readings on the variable joints would be of little value. With these two sets belongs the second dip set found in other localities.

JOINTS OF THE ENTIRE REGION

Fig. 5 is a tabulation of all the strikes read throughout the Ithaca district, over three thousand in number. They are arranged in groups of five degrees each. It must be remembered that, with the exception of the six hundred also shown in Fig. 4, these joints were selected, so that the figure does not give a true record of the numerical occurrence of the various strikes but rather of the relative importance of the joints in each direction.

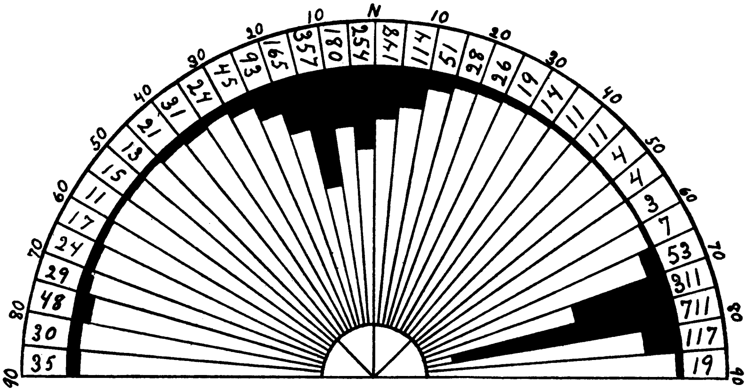


Fig. 5.—Tabulation of the strikes of the joint planes of the Ithaca region

Strike Joints.—In the Ithaca region the strike set is the most important. Fig. 5 shows that for the entire area studied far the greater part of all the joints which may be considered as belonging to this set do not vary more than ten degrees in strike. As the figure shows, there is almost no tendency for the strike set to grade into the minor joints at each side. This set is even more sharply defined and easily recognizable in the field.

The area studied was divided into squares of about a quarter of a mile on an edge. For Fig. 6 the readings of the strike joints in each small area were averaged together and the average is given beside a line drawn in the average direction. The center of the line is in about the center of the area considered and the width of the line is proportional to the number of readings included in the average. A width equal to half a mile on the scale represents one hundred readings. Where the joints in any area vary in direction more than is usual in this set the average direction is given in light figures. Where the variation is less than usual the figures are heavy. It will be seen from Fig. 6 that the average directions are nearly parallel to the axes of the folds. It is noticeable that for the four localities along Salmon Creek, where this set is well developed, the average directions do not vary half a degree, though the individual readings vary by several degrees. There is a certain actual variation from place to place not due to the thoroughness with which observations were made. For example, just south of Crowbar Point and also on the opposite side of the lake the average angle is unusually low even though the number of readings is sufficient to give a reliable average. The cause of such deviations probably lies in the local variations of the forces producing the folds and joints. Near the Shurger Point anticline, which rises to the east so that the strike of the rocks is not parallel to the axis, the average strike of the joints does not turn so that it is parallel to the strike of the rocks, but in the opposite direction so that the strike of those south of the axis points slightly in toward the center of the domed anticline. Just how the strike joints vary with the pitching of folds cannot be determined from this one region. Further study of well-developed strike joints near pitching folds is necessary to warrant conclusions. In the southern part of the area studied the strike set is too poor to give reliable evidence.

Effect of the rock character.—The variation between the two averages near the mouth of Taughannock Creek is due to the character of the rock. The upper readings were in the Tully limestone, the lower in the Hamilton shales directly beneath the limestone. Few readings were made in the Tully elsewhere but a similar variation from the strike in the shales was noticed in other places. The hardness of the rock has a decided effect on the strike joints. They seem best developed in homogeneous shales, especially the Hamilton beds. This is partly indicated by the abundance of readings on this set in the northern part of the map. South of the lake the rocks are hard Portage sandstones and shales, and the meagerness of readings, though partly due to poorer rock outcrops, fairly indicates the lack of development of this set. At Enfield Falls this set is fairly good and at Forest Home on Fall Creek it is well developed. The same effects may be seen in one locality. At Forest Home there are alternate shale and sandy layers. The strike joints are better developed in the shales and the dip joints in the sandy beds. If the contact between the two kinds of rock is sharp both sets often cease at the contact, the strike joints passing only through the shale and the dip joints only through the sandstone. In other places a change in hardness was found to affect the strike joints, sometimes causing them to cease abruptly.

Often where the strike set is poorly developed in the harder Portage beds the set striking a little north of west is unusually well developed, almost replacing the genuine strike set. This set appears mainly in the harder rocks. It is apparently not of the same origin as the strike set, since it is always less uniform even where stronger. This is well illustrated in Lick Brook where the conspicuous joints are the two dip sets and the westerly set. The westerly joints have a large hade and are not uniform but the strike joints, though few, are nearly vertical and more regular.

Hade of the strike joints.—In comparing the joint planes and folds more can be learned from the hade than from the strike. In Fig. 6 the second part of the statement of each average indicates the average hade. If the number is heavy it means that the angle of hade varied only a few degrees; if light, that the angle varied over ten or fifteen or more degrees. A light letter indicates that part of the readings were to the north and part to the south. A heavy letter means that nearly all were in one direction or the other, and the heaviest lettering that none were in the opposite direction. The average number is taken from the algebraic sum of the north and south readings.

In the region of the Enfield syncline most of the readings were slightly to the south, though only those at Enfield Falls were very reliable. At the southern border of the area the few readings taken were so variable that they averaged 0°. Between the axes of the Watkins anticline and Corbett Point syncline the strike joints are poor for reading of hade in most places. In many cases the outcrops do not permit a reliable reading and in most places the hade is variable. Fig. 6 shows that many of the variable areas give averages to the south but the areas of greater constancy usually show averages to the north. The only really good area of strike joints in this district is at Forest Home. There, out of 146 readings only two were to the south. It is fair to assume that on the northern limb of the Watkins anticline the tendency is to the north.

From the axis of the Corbett Point syncline northward for about three miles the tendency is to the south. On the eastern side of the lake the readings are nearly all to the south from a point somewhat south of the axis of the syncline to a point about three-fourths of a mile north of Esty Glen (locality 43). On the western side the readings are more variable but the areas of more numerous and constant readings are strongly to the south. North of this is a region of variable joints on both sides of the lake. On the eastern side the three zeros represent one average of exactly zero and two averages of small fractions to the north. Just south of Shurger Point the readings are mostly to the south, north of Shurger Point they are variable with an average of about half a degree to the north. Just south of the anticlinal axis they are again nearly all to the south. Much the same thing occurs on the western side but there the northerly tendency predominates. Judging from the other folds a small change in the dip of the rocks, not sufficient to reverse the direction of dip or even to make the beds horizontal, might explain the behavior of the joints. Such a flexure might be local or a continuation of a fold dying out here. On the eastern side this turns the hades slightly to the north for a short distance but the general southerly tendency predominates. On the western side this flexure acts as if it merged with the main axis, either reversing the readings or making them variable from a point south of Crowbar Point to the main axis. Continued folding after the formation of the joints would also explain this irregularity. South of the axis of the fold the average hades to the north are so small that if the plane of the bedding instead of the horizontal were used as a datum plane the averages in most cases would be to the south.

North of the axis of the Shurger Point fold the hades are unusually uniform and satisfactory. Along the shore north of Salmon Creek the cliffs are talus covered and falling where acces-

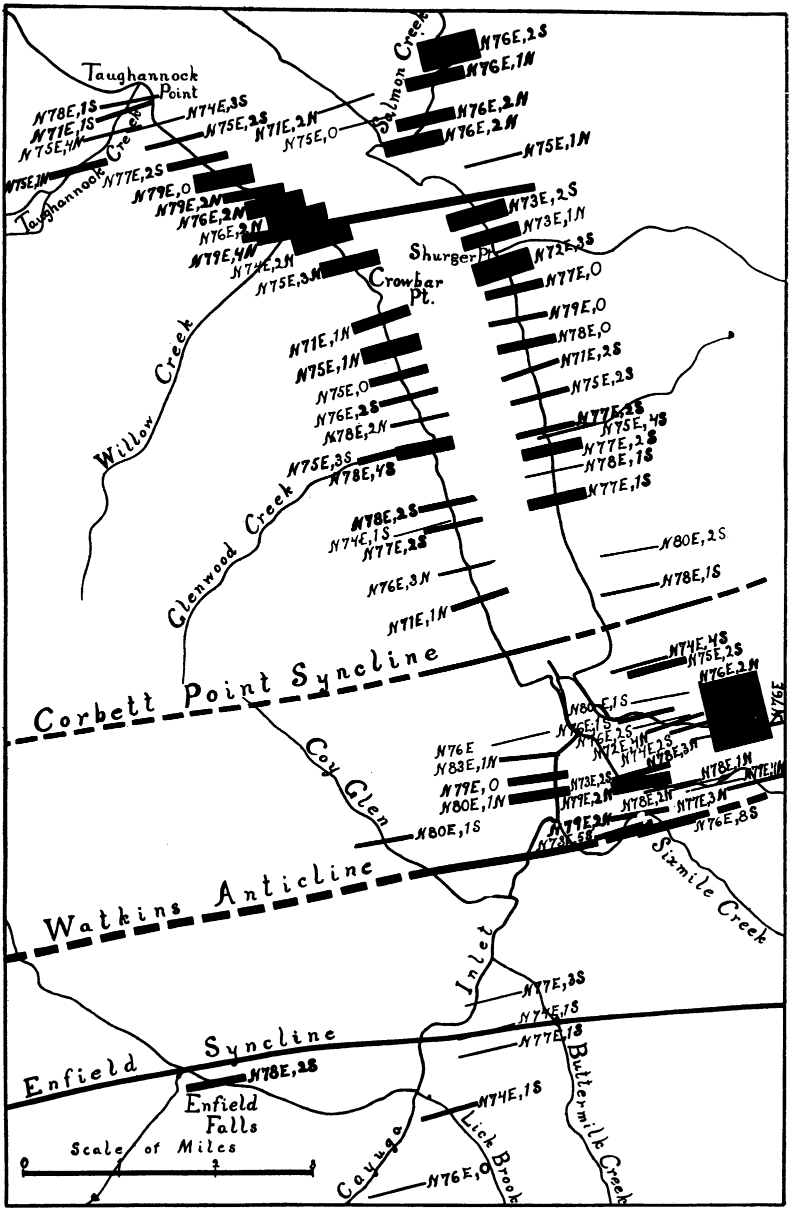


FIG. 6.—The axes of the folds and the average strikes of the strike joints

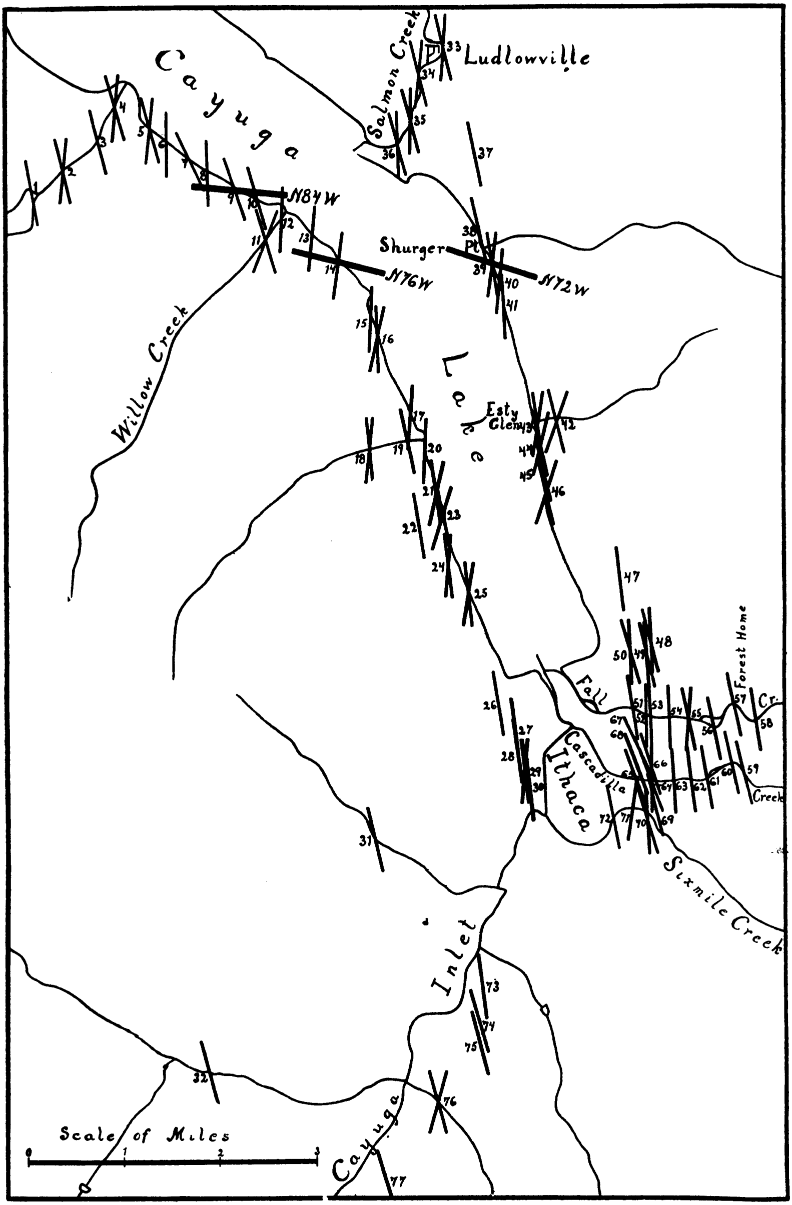


FIG. 7.—The strike of the faults and the average strikes of the dip joints

sible, so that the few readings made there are unreliable, but they are mostly to the north. On the eastern side of the lake the first area north of the axis and the first three in Salmon Creek show no readings whatever to the south, though the most northerly of the three shows a few zeros. Out of 61 readings at the fourth locality only one is to the north. There are a few zeros and the rest are to the south. Evidently there is a sharp reversal of the hade between the third and fourth localities. Because of a break in the rock wall at this point the transition only appears in the few variable readings at the adjacent localities.

On the western side of the lake no readings to the south appear for three-fourths of a mile north of Willow Creek. Then after an interval of transitional variable hades the readings are all to the south as far as Taughannock Point. The observations from the Taughannock gorge are not reliable for hade. Those in the lower part of the gorge are mostly from outcrops of slight vertical exposure, and near the falls (locality 2) the large amount of faulting and recent slipping make the readings untrustworthy. The hades just north of Willow Creek are small and are unusually uniform numerically. Between Willow and Taughannock creeks the reversal of hade takes place about where the dip of the beds changes from a strong dip to the north to horizontal. The steeper dip is resumed near Taughannock Point. On the eastern side of the lake a hard layer of rock was found to be nearly horizontal at the place where the hade of the joints is to the south but the variation in dip of the rocks was not traced. Evidently the sharp change of hade at the edge of Ludlowville is in a syncline.

Thus it appears that, in general, the inclination of the strike joints is in the same direction as the dip of the rocks or rather is such that, if the planes of the joints were produced, they would meet above anticlines and below synclines. The better developed the joints and more uniform the hade the more nearly true this is. Even folds not strong enough to reverse the direction of dip reverse the joints.

DIP JOINTS.—Next in importance are the dip joints. In the upper Fall Creek gorge there is a strong set of joints nearly at right angles to the strike set. In most of the other localities it was found

EXPLANATION OF FIG. 7

Locality	No. of Readings	Average Strike	Constancy	Average Hade	Constancy
1.	4	N. 10° W.	High	2° W.	High
2.	20	N. 14 W.	Low	5 E.	Low
	7	N. 5 E.	Fair	7 E.	Fair
3.	4	N. 15 W.	Fair	1 E.	High
4.	9	N. 17 W.	Fair	1 W.	High
	7	N. 5 E.	Fair	0	High
5.	1	N. 16 W.	. . . .	3 E.	. . . .
	1	N. 6 E.	. . . .	0	. . . .
6.	2	N. 1 W.	Fair	1 W.	Fair
7.	9	N. 26 W.	Low	3 E.	Low
8.	3	N. 2 W.	High	3 W.	Fair
9.	7	N. 19 W.	Fair	0	High
10.	10	N. 17 W.	Fair	0	High
11.	6	N. 17 W.	Fair	3 E.	Fair
	7	N. 21 E.	High	0	High
12.	4	N. 2 E.	High	1 W.	Fair
13.	32	N. 5 E.	Fair	1 W.	Fair
14.	25	N. 7 E.	Fair	2 W.	High
15.	4	N. 2 E.	High	1 W.	High
16.	12	N. 2 W.	Fair	2 E.	Low
	2	N. 12 E.	Fair	0	High
17.	3	N. 3 E.	High	2 W.	Fair
18.	20	N. 6 W.	Fair	0	Fair
	7	N. 5 E.	High	0	Fair
19.	24	N. 13 W.	High	0	High
20.	1	N. 1 E.	. . . .	. . . .	. . . .
21.	4	N. 9 W.	Fair	0	Fair
	5	N. 12 E.	Fair	1 W.	Fair
22.	16	N. 10 W.	Low	6 E.	Low
23.	10	N. 12 W.	Low	0	Low
	3	N. 16 E.	Fair	2 W.	High
24.	4	N. 8 W.	Fair	0	Fair
	7	N. 3 E.	Fair	2 W.	Low
25.	4	N. 7 W.	High	1 E.	High
	6	N. 8 E.	Low	2 E.	High
26.	15	N. 10 W.	Fair	2 E.	Fair
27.	21	N. 9 W.	Fair	3 E.	High
28.	2	N. 10 W.	Low	7 E.	Low
29.	8	N. 7 W.	Fair	11 E.	Low
	16	N. 3 E.	Fair	3 E.	Low
30.	13	N. 7 W.	Fair	3 E.	Fair
31.	3	N. 14 W.	Fair	1 E.	Low
32.	8	N. 16 W.	High	1 W.	High
33.	9	N. 14 W.	High	0	Fair
	78	N. 4 E.	Fair	2 E.	Low
34.	5	N. 13 W.	Fair	1 E.	Fair
	19	N. 8 E.	Fair	4 E.	Fair
35.	14	N. 15 W.	High	0	High
	22	N. 1 E.	Low	9 E.	Fair
36.	2	N. 15 W.	Fair	9 E.	Low
	29	N. 1 W.	High	12 E.	High
37.	6	N. 14 W.	Fair	1 E.	High
38.	5	N. 15 W.	High	2 E.	High

EXPLANATION OF FIG. 7—*Continued*

Locality	No. of Readings	Average Strike	Constancy	Average Hade	Constancy
39..........	2	N. 9 W.	Fair	15 W.	Fair
	14	N. 7 E.	Fair	5 W.	Fair
40..........	6	N. 5 E.	Low	1 W.	Fair
41..........	6	N. 3 W.	High	1 W.	High
42..........	1	N. 14 W.	....	1 W.	....
	2	N. 19 E.	Fair	1 W.	High
43..........	6	N. 9 W.	Fair	0	Fair
	3	N. 8 E.	Fair	1 W.	Low
44..........	3	N. 14 W.	Fair	2 W.	High
	5	N. 13 E.	Fair	0	Fair
45..........	2	N. 15 W.	High	1 W.	High
46..........	22	N. 14 W.	High	0	High
	1	N. 17 E.	....	0	....
47..........	7	N. 8 W.	Low	0	Fair
48..........	1	N. 15 W.	....	4 E.	....
	5	N. 5 W.	Fair	3 W.	Fair
49..........	12	N. 14 W.	High	1 W.	Low
	8	N. 5 W.	Fair	3 W.	Low
50..........	1	N. 17 W.	....	1 E.	....
	3	N. 3 W.	Low	2 W.	Fair
51..........	17	N. 10 W.	Fair	1 W.	Fair
52..........	11	N. 3 W.	High	2 W.	High
53..........	9	N. 1 W.	Low	2 W.	Fair
54..........	91	N. 2 W.	Fair	1 W.	High
55..........	43	N. 12 W.	Fair	1 E.	Fair
	17	N. 4 E.	Low	0	High
56..........	5	N. 12 W.	High	0	Fair
57..........	109	N. 12 W.	High	0	High
58..........	16	N. 9 W.	Fair	1 E.	High
59..........	9	N. 14 W.	High	0	Fair
60..........	29	N. 13 W.	High	0	Fair
61..........	13	N. 11 W.	High	1 E.	High
62..........	25	N. 7 W.	Low	3 W.	Low
63..........	44	N. 5 W.	High	2 W.	Fair
64..........	15	N. 22 W.	Fair	1 E.	Low
	2	N. 2 W.	Fair	2 W.	Fair
65..........	51	N. 22 W.	Fair	0	Low
66..........	4	N. 19 W.	High	4 W.	Fair
67..........	19	N. 26 W.	Fair	9 W.	Fair
68..........	57	N. 22 W.	Fair	6 W.	Low
69..........	2	N. 15 W.	High	3 E.	High
70..........	22	N. 18 W.	Fair	12 E.	Fair
	9	N. 5 W.	High	0	Fair
71..........	1	N. 8 E.	....	2 W.	....
72..........	23	N. 12 W.	Low	14 E.	Fair
73..........	11	N. 9 W.	Low	2 E.	High
74..........	2	N. 18 W.	Fair	1 E.	High
75..........	2	N. 16 W.	High	2 E.	High
76..........	9	N. 15 W.	High	0	Low
	3	N. 15 E.	Low	9 E.	Low
77..........	1	N. 18 W.	....	2 W.	....

that the dip joints do not belong to a single set. They fall into two groups, with sometimes one and sometimes the other more prominent. Practically all the strong regular joints of small hade which do not belong to the strike set lie in the general direction of the dip of the rocks, but a curve drawn between the compass directions and the number of joints striking in each direction for a locality will usually show a tendency toward two maxima. That is, the dip joints form two groups with the average of one group nearly perpendicular to the axes of the folds, somewhat west of north, and the average of the other set farther east. There may be readings continuously between the two averages, or there may be a gap with no readings in the middle. There is a decided bunching of strikes toward the extremes rather than a larger number of readings near the average value of all the dip joints.

The strike joints show no such tendency. With them a curve between strikes and number of readings has a decided maximum near the median value with the number of readings decreasing rapidly toward the extremes. In one or two places strike joints were seen crossing each other, that is, fairly strong joints with directions near the extreme range for the strike set would occur at the same place and consequently intersect, but this is rare and the strike joints clearly form a single set. The dip joints often cross each other. In many areas only one dip set occurs, as is shown in Fig. 7. In such places it is usually found that the average of all the dip joints is about the same as one of the averages obtained by dividing the readings where both sets occur, thus justifying the division in the latter case. In better cases both dip sets occur together strongly and nearly equally developed, the two sets making so large an angle with so few intermediate joints that one would not consider averaging them together as a single set.

Around the city of Ithaca the more westerly of the dip sets is dominant. Northward the more easterly set is often the stronger. At Lick Brook the two sets are about equal and do not intergrade. With the set north of west they cut the rocks into conspicuous triangles instead of the more common parallelograms where only one dip set is strong. Southward from Esty Glen the dip sets are about equal, the angle between them is comparatively large, and each set has only a fair range of strike so that the two are entirely distinct. The line of the cliff lies between the two sets and the cliff face is in many parts composed of projecting and re-entrant angles formed by the joint faces of large area meeting in obtuse angles. The small number of readings made in that locality is due to the fact that these joints are mostly at inaccessible heights in the cliff. The directions are rather constant, however, so that the readings made are representative of all.

The angle between the dip sets varies. Some of the averages in Fig. 7, which strike nearly north, come from observations too few in number to justify division into two sets. The resulting median value does not correctly represent either set if both are present. In other places, such as lower Fall Creek, there is a well-developed set whose average is nearly north, so that the angle between the two sets is only a few degrees. The upper locality at Willow Creek shows an unusually wide angle between the set. Those readings were made in the Tully limestone, and in the dip joints as in the strike joints the hardness of the rock seems to affect the direction. Unlike the strike set, the dip joints are better developed in the sandstones than in the shales. This appears where such layers alternate and also in the general distribution of the dip sets. In some of the softer shales along the lake they are rare and they are seldom so well developed there as the strike set. In the hard Portage rocks from the end of the lake southward the dip sets are far stronger than the strike. The conspicuous joints seen in the gorges in the city of Ithaca are dip joints.

The direction of the dip joints and the angle between the two sets seems to depend on the general force which caused the folding and the angle which the variable local resultant force made with it. The two sets seem to be arranged on each side of a line which is a compromise between the two. The range of the dip joints is from a line nearly perpendicular to the axes of the folds around to the east toward the perpendicular to the strike of the faults. The small angle between the sets near the city is probably related to the lack of strong folding there. In Fig. 5 the dip sets of the different areas overlap, obscuring their double nature.

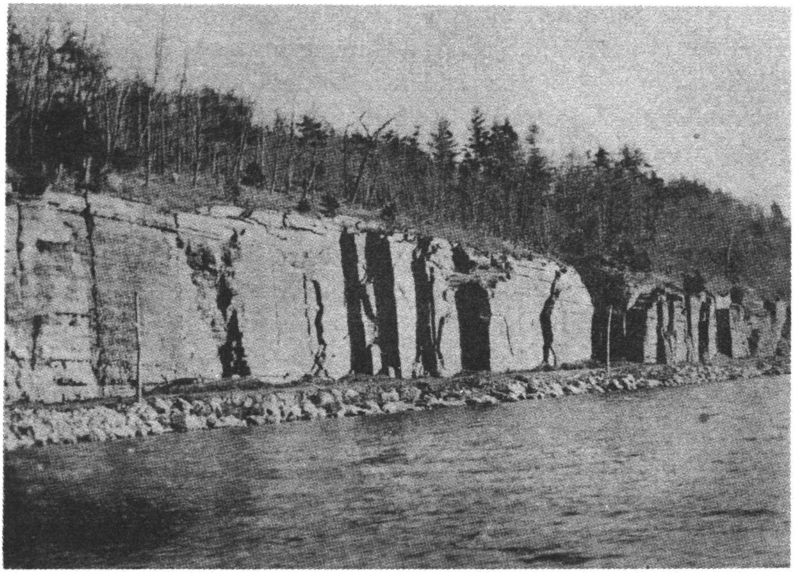
Hade of the dip joints.—The hade of the dip joints is in general larger and less uniform than in the strike joints. In some places in the Portage rocks where the dip joints are strong and occur at regular intervals, forming joint-faced buttresses along the gorge walls, the angle is quite uniform and nearly vertical. These evenly spaced joints occur in Fall Creek, Glenwood Creek, and in the Portage beds in the Taughannock gorge.

A detailed study of the pitch of the folds is necessary before the meaning of the hade of the dip joints will be clear. In general the hade of the joints and pitch of the rocks seem to be in the same direction, though some local measurements were opposite. The joints as a rule are not perpendicular to the bedding planes.

Some of the larger angles of hade are associated with faulting. This is true along University Avenue in Ithaca (localities 67 and 68). It is more conspicuous at Taughannock Falls where joints with a vertical exposure of two hundred feet or more are nearly vertical at the top of the gorge wall and bend to an unusually large angle with the vertical near the base where several nearly horizontal faults are present. This is probably due to drag along the faults.

Minor Joints.—Besides these fairly constant sets there are minor joints striking in every direction, but they are as a rule easily distinguished from the major sets by the fact that few of them are to be compared with the major joints in strength and especially by their irregularity and usually large hade. Near the Shurger Point anticline is a set of minor joints which are comparable with the major sets in strength. These joints vary widely in direction, but ordinarily make a fair angle with the strike and dip sets and always have a large inclination, from 30° to 60°. The strike is both N.E. and N.W. and the hade may be to either side in the joints of either direction. High-angled joints similar to these were seen in other parts of the area studied but usually not so well developed. In Salmon Creek highly inclined joints of about this strength are frequent but their direction is nearly the same as that of the regular strike set. In fact, some of them seem to be continuous with strike joints which are nearly vertical for part of their height, then suddenly bend to a high angle and probably change their direction somewhat also. Measurements on these joints are only approximate because the exposures are usually poor. The rock walls quickly fall where these large diagonal planes for slipping are present. These highly inclined joints are not uniform in direction and a single joint is usually a curved instead of a plane face. They seem to be associated with the stronger folding.

Among the smaller joints of interest are certain offshoots from the dip joints. In an area where nearly all the dip joints belong to one set but where there is an occasional example of the other set, or where the dip sets vary from their usual direction, the less usual joints sometimes have small cracks running off diagonally for a few inches in the more common direction of the dip joints.



Photograph by G. D. Harris

FIG. 8.—Jointing on the east shore of Cayuga Lake. The joints are not at right angles to the stratification but are inclined in the same direction as the beds.

Of the joints with no apparent uniformity perhaps the most interesting are the smallest. Some of the rocks, especially the Hamilton shales, are broken by a mass of tiny, smooth, curved faces of only a few inches in area. These are the faces along which the shale parts when it crumbles. They have no apparent system.

Joint planes are present in all sizes from an inch to two or three hundred feet in length and height but there is not an even gradation from one to the other extreme. The joints are divided into groups and each group shows distinct characteristics.

The strike and dip relation of the master joints of this region has been generally observed and readings have been made on the directions of the joints, chiefly by C. G. Brown whose data were used by Professor Hobbs.[1]

INFLUENCE OF JOINTS ON TOPOGRAPHY

The joint planes of this region have a marked influence on the form of gorges, cliffs, and waterfalls. The joints in the cliff along Cayuga Lake were made famous by the illustrations of Hall and Dana. Fig. 8 is a photograph of some of these joints at locality 46, Fig. 7. Their effects on gorges and waterfalls have been illustrated and described many times.[2] The rapidity of erosion seems greater where the strongest joints are transverse to the general stream direction rather than parallel to it. In the latter case small streams often follow a very narrow channel between two parallel joint faces. Where the transverse joints are strong and there are one or more sets nearly parallel to the stream, there are often broad chambers in the gorge with the walls formed by the larger joint faces and the stream entering and leaving by narrower openings. These may be seen in upper Lick Brook and in other gorges in the hard Portage rocks. The similarity between some of the larger features of drainage and the directions of the joint planes seems to be due to the fact that the streams were once consequent upon the same uplift with which the joint planes are associated.

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[1] W. H. Hobbs, *Jour. Geol.*, XIII, No. 4 (1905), 363–74.

[2] R. S. Tarr, *Bull. Amer. Geog. Soc.*, XXXVII (1905), 193–212; *Pop. Sci. Mo.*, LXVIII (1906), 394–96; *U.S. Geol. Surv.*, *Folio 169*, p. 3; field edition, pp. 24–25; *New Physical Geography; Physical Geography of New York State;* W. H. Hobbs, *Jour. Geol.*, XIII, No. 4 (1905), 363–74.

[*To be continued*]